DEVELOPMENT OF A BROADBAND UNDERWATER SOUND PROJECTOR

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Abstract - An underwater sound projector has been recently developed for operation over a decade long frequency range. The output of the projector has been designed for 10 kHz to 100 kHz operation on an autonomous underwater vehicle (AUV). The transducer is resonant at 100 kHz but has been designed to deliver high sound pressure levels without impedance or phase instabilities. The transducer features the first successful stacking of 1-3 piezocomposite materials. The selection of the 1-3 piezocomposite materials has resulted in the mode-free sound output while the stacking arrangement permits acoustic operation with twice the sound output at half the resonance frequency of a single layer. The stacking is done mechanically in series and electrically in parallel with the center electrode as the positive plane. Furthermore, the center electrode has been segmented into four individual elements such that combinations of the sectors offer the ability to access nine different apertures.

I. INTRODUCTION

The Naval Research Laboratory (NRL) has completed the design, fabrication and initial in-water acoustic evaluation of a prototype underwater projector. This sound source has been designed for replacement of limited bandwidth tonpilz projectors on an autonomous underwater vehicle (AUV).

Recent underwater acoustics research interests have identified improved underwater acoustic minehunting capabilities by upgrading SONAR systems to broadband frequency operations [1]. The advantage of operating over a wide band is to classify underwater targets by their specular acoustic resonant scattering signatures. This capability has theoretically shown benefit in improved imaging for underwater structure characterization and identification. The AUV system configuration using this projector has been designed for two horizontal acoustic beams (1λ and 2λ apertures) in order to accomplish multi-aspect operation and acoustic motion compensation. These apertures have been selected so that the SONAR can realize a 3-inch resolution of the underwater structures [1]. The implementation of multioctave frequency systems have recently progressed with the introduction of new digital electronic techniques because these are able to handle large amounts of data for efficient processing in real time. However, the advancement of underwater sound projectors has typically been a limiting factor for realizing the potential system gains that the digital data processing schemes offer. Traditionally, underwater projectors have been used solely at their resonance frequency with a limited bandwidth of -3 dB about this frequency. This has resulted in projectors useable only at discrete frequencies with limited bandwidth. Although there are some electronic means for "tuning" projectors to behave with additional electrical resonance

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frequencies, this approach will often result in system instabilities in terms of the electrical impedance magnitudes and phase. These instabilities cause problems in terms of limitations of the data processing. A solution to this is the use of an acoustic projector capable of mode-free (no instabilities) decade frequency operation.

The NRL underwater acoustic projector has been developed for 10 kHz to 100 kHz operation in a synthetic aperture SONAR minehunting AUV, however, the design of this projector will also permit it to be used in other side scan applications.

The transducer is resonant at 100 kHz but has been designed to deliver high sound pressure levels without impedance or phase instabilities. The transducer features the first successful stacking of 1-3 piezocomposite materials. This stacking was accomplished through precision alignment of the individual piezoceramic components. Prior to this development, 1-3 piezocomposite materials have been used in transduction applications such as low frequency hydrophones and high frequency, near-field biomedical electronics. Because of the difficulty in stacking the individual layers, projector use has not been pursued. However, the fact that the material configuration of the 1-3 piezocomposite results in a wide band frequency response void of lateral plate modes, makes this material attractive for wideband transmit application. The objective of the NRL development was to exploit the wideband response and use transducer design techniques to enhance acoustic output.

II. BACKGROUND

Current mine detection and classification systems use existing transducer designs, such as the tonpilz (piston) transducers. This type of design has been selected to provide a maximum source level at 20 kHz with high efficiency and reliability as well as excellent directivity responses. The manufacturing of the tonpilz transducer is an expensive process since each element is manufactured through hand assembly. The pairing of each element is then matched into a final arrangement by matching the electrical and mechanical characteristics of each transducer such that a final array of elements is well matched by a prescribed array configuration. This means that a number of extra elements are fabricated in order to do the element sorting. Because of the hand assembly and sorting, the final cost of a 2 by 4 array (8 elements) configuration is high. Furthermore, the utilization of this transducer comes at a performance cost in terms of operating frequency (20 KHz) and operating bandwidth (< 10 kHz). The tonpilz has the advantage of high source level (> 220-dB at f_R) but in the shallow water environment of the AUV, source level requirements are typically no more than 210 dB because of reverberant nature in shallow water environments.

III. PROJECTOR DESIGN SPECIFICATIONS

A set of system specifications and desirable features is presented in Table I. Note that the specified operating band is over a decade frequency range as opposed to the current discrete operation of the tonpilz approach.

TABLE I

Projector Performance Goals

Operating Frequency Band: 10 kHz to 100 kHz

Source Level (minimum at 10 kHz): 190 dB for full aperture

Source Level (from 20 kHz to 100 kHz): Constant 200 to 210 dB for full aperture

Linear electrical phase response over the operating frequency band

Projector Radiating Face (vertical by horizontal): $2\lambda \times \lambda$ = 6" by 3" (for full aperture)

Element Radiating Face (vertical by horizontal): $1\lambda \times \lambda/2$ = 3" by 1.5" (for one element)

Projector Array: 2 by 2 elements with an electrode arrangement to option either the one element or full aperture directivity selection

Thin plate geometry for minimum protrusion into the AUV interior volume

Monolithic structure mounting with prescribed element aperture definition

IV. DESIGN CONCEPT

The design concept of the NRL projector is to operate below the thickness resonance frequency of the 1-3 piezocomposite material. Since a single layer of 0.25-inch thick 1-3 piezocomposite material has a thickness resonance of approximately 200 kHz, NRL chose to mechanically stack two layers together such that the total thickness resonance is half. This means that the upper operating frequency should be 100 kHz. A key to this approach is to utilize a piezocomposite material structure that will output high acoustic source levels without introduction of spurious modes within the band of 10 kHz to 100 kHz. The performance cost for this type of operation is in the peak source level, however, through design means an acceptable output level can be achieved.

Fig. 1 shows the assembly drawing of the NRL projector. As shown, there are two layers of 1-3 piezocomposite plates stacked mechanically in series and electrically in parallel with the positive electrodes in the center. An advantage realized through this design is that the thickness resonance frequency is lowered from 200 kHz to 100 kHz, which is the dictating upper frequency limit of the transducer. The parallel electrical wiring also provides several benefits; one is to increase the acoustic output by a factor of 2, which correlates to a +6 dB increase in the source level over that of a single 1-3 piezocomposite plate. This is because the transducer is thicker (which is why the resonance frequency is half for two layers) and there is now a doubling of acoustic displacement for the same voltage across each layer because the electrical impedance is similarly half that of a single layer. There is also minimal stray capacitance losses and therefore minimal EMI noise radiation since the two outer electrodes are electrical ground planes. This factor becomes important when considering other system components because it means that there is no electrical and magnetic stray noise radiation. The electrodes of the 1-3 piezocomposite have been electroplated copper with a thin gold covering for corrosion protection.

Although the concept of mechanically stacking is not unique to transducer design, prior to this transducer the 1-3 piezocomposite material had not been successfully stacked to realize the performance gains. Past efforts have resulted in stacked transducers exhibiting traits indicative of single layer operations. That is, transducers showed resonate frequency behavior of the single layer thickness mode and did not show the doubling of acoustic output. A reason for this is that to realize the potential of stacking it is necessary to assure that the individual piezoceramic rods of both layers are properly stacked on top of each other as opposed to aligning a rod on top of the softer host matrix material which does not provide an acoustic hard boundary condition.

Within the assembly drawing of Fig. 1, a 0.5-inch thick tungsten backing plate may be seen. The addition of this plate results in an acoustic hard boundary condition. If the backing was a perfectly rigid base, then theoretically the acoustic gain to the source level will be +6 dB as compared to an acoustic soft boundary condition such as air. Fig. 2 shows an analytical plot of the influence of the thickness of a tungsten backing plate as computed using a 1-D wave propagation model [2]. It was determined that since the overall weight of the projector was NOT an issue, that the 0.5-inch tungsten backing should provide +5 dB gain, however, it should also be noted that if weight was of concern, then a 0.25-inch thick tungsten backing should provide greater than +4 dB gain (Fig. 2 shows a plot of the backing material thickness and its influence on acoustic source gain over the operating frequency band). The acoustic gain for the 0.5-inch thick tungsten plate results in a 90% forward efficiency of the sound energy as well as wideband frequency band coverage. This was the only candidate backing material that provided the acoustic gain over the complete frequency decade of interest. Further investigation of this backing showed that this geometry and size has minimal to non-existent modal contamination over the operating frequency band.

To prevent acoustic excitation into the AUV structure, a frame was fabricated of a decoupling material consisting of lead-loaded silicon polymer particles placed into a syntactic foam host matrix. Measurements on the decoupling material have shown an insertion loss level of 8 dB/inch at 10 kHz to 26 dB/inch at 20 kHz up to 40+ dB/inch at 100 kHz. These levels of insertion loss help ensure high mechanical and acoustical isolation between the projector and the AUV structure.

The sides of the 1-3 piezocomposite active layers are edged with 0.25-inch corprene strips. Corprene is a cork board type of gasket material that acoustically behaves as an acoustic soft boundary for low hydrostatic pressure applications such as

shallow water. This results in a pressure release condition such that lateral acoustic pressures are absorbed and the resulting acoustic radiation directivity patterns approach theoretical expectations for a baffled rectangular piston. The corprene also provided a fabrication ease for soldering the wires onto electrode connections on the sides of the piezocomposite sandwich.

To ensure that the electrical connections can withstand a high voltage drive level, four separate positive connectors were used with the tungsten backing plate positioned as an electrical ground. Each element aperture has its own connector (Brantner SEA-CON XSA waterproof connector) which may be addressed through rear connections. This concept ensures that there will be no voltage or dielectric cable breakdown between the tuning step-up transformer and the individual element aperture. It also ensures that there is no radiating EMI (or crosstalk) coupling within the connectors that can interfere with other system components. The location of the connectors was selected to fit within the existing tonpilz holes such that there will be minimal need for machining of the shell during the projector installation.

Fig. 3 is a photograph of the completed unit with a polyurethane face encapsulation for in-water acoustic evaluations. The complete transducer was designed such that it could be tested in-water as a stand alone package. Each aperture may be addressed or all four apertures can be connected together in parallel for full $2\lambda \times \lambda$ aperture.

V. TEST RESULTS

During each of the fabrication steps, impedance data were measured to ensure that the expected performance was being realized. This in-air data was maintained from procurement of the original plates, bonding of the plates into the layered configuration and attachment of the backing plate to the finished transducer. Fig. 4 is the impedance plot for each $1\lambda \times \lambda/2$ aperture as measured for the complete projector of Fig. 3. This Fig. shows the electrical impedance resonance frequency occurring at 98 kHz for each element. The responses of the apertures are all well behaved and in close agreement in terms of both impedance and frequency response. Also note that there is no apparent resonance frequency behavior at the individual layer frequency of 196 kHz. This is an indication that the individual rods in the 1-3 piezocomposite layers have been well aligned on top of each other such that characteristics of the single layer are not present. There is a mode present in the 30 kHz to 40 kHz region which was first noticed when the backing mass was attached onto the piezocomposite sandwich. This mode is related to a mass resonance of the sandwich and backing plate.

Table II is a listing of the capacitance and dissipation as measured at 1 kHz for each aperture as well as the full beam. Note that the capacitance differences between the individual apertures is minimal which is also a positive indication of good element definitions within the electrode striping.

TABLE II
Projector Capacitance & Dissipation
(at 1 kHz)

Aperture #	C (pF)	tan δ (%)
1	4825	1.9
2	5006	1.8
3	5004	1.9
4	5041	1.8
Full	19,877	1.8

The NRL projector was measured in-water at the NUWC/USRD Lake Gem Mary facility in Orlando, FL, in August 1996 [3]. A plot of the measured transmitting voltage response (TVR) is shown in Fig. 5. The TVR is the response normalized for a 1 Volt drive, where the source level (SL) can be computed by adding onto the TVR response. For a 2,000 V drive, the SL will be 66 dB higher than the TVR. This means that the response at 10 kHz should be 192 dB and then rise to 207 dB at 20 kHz. Above 20 kHz an active transformer is presently being designed to roll-off the drive voltage by 12 dB/octave in order to maintain a constant source level as preferred by the specifications of Table I. As with the immittance plots, the TVR shows the 30 kHz mode as well as the 100 kHz thickness resonance and a lateral resonance at 7 kHz. The 30 kHz backing plate mode actually causes an increase in

acoustic output in the lower frequency regions by approximately 6 dB. In addition to the measured TVR, transmit directivity patterns were conducted in both planes at 10 kHz, 20 kHz, 50 kHz, and 100 kHz for each aperture as well as for all four apertures in parallel. Table III lists the vertical (XZ-plane) and horizontal (XY-plane) -3 dB down point beamwidths of each aperture, the full aperture and the current tonpilz projector. Fig. 6 shows the measured in-water horizontal directivity response at 20 kHz for the full aperture beam. Note that this response is representative of the other directivity patterns where excellent symmetry and beam profile are realized.

The full aperture, in particular, is within the system requirements but the single apertures show some variation, although they are still within specifications. The behavior of all the patterns improve to text book quality as frequency is increased.

TABLE III
Measured Beamwidths (-3 dB) at 20 kHz

Aperture #	Vertical	Horizontal
Theoretical single	50	100
1	61	90
2	49	99
3	49	94
4	41	98
Tonpilz element	59	--
Theoretical Full	24	50
NRL Full	21	51
Tonpilz Full	27	51

CONCLUSION

A wideband projector has been designed, fabricated and tested for application on a minehunting AUV. The results show that this transducer shall meet system needs as established in the requirements of Table I. Research is continuing with integration of the projector into the current system described in [1]. This system integration will include an active transformer to provide a constant source level of acoustic output over a decade long operating frequency range.

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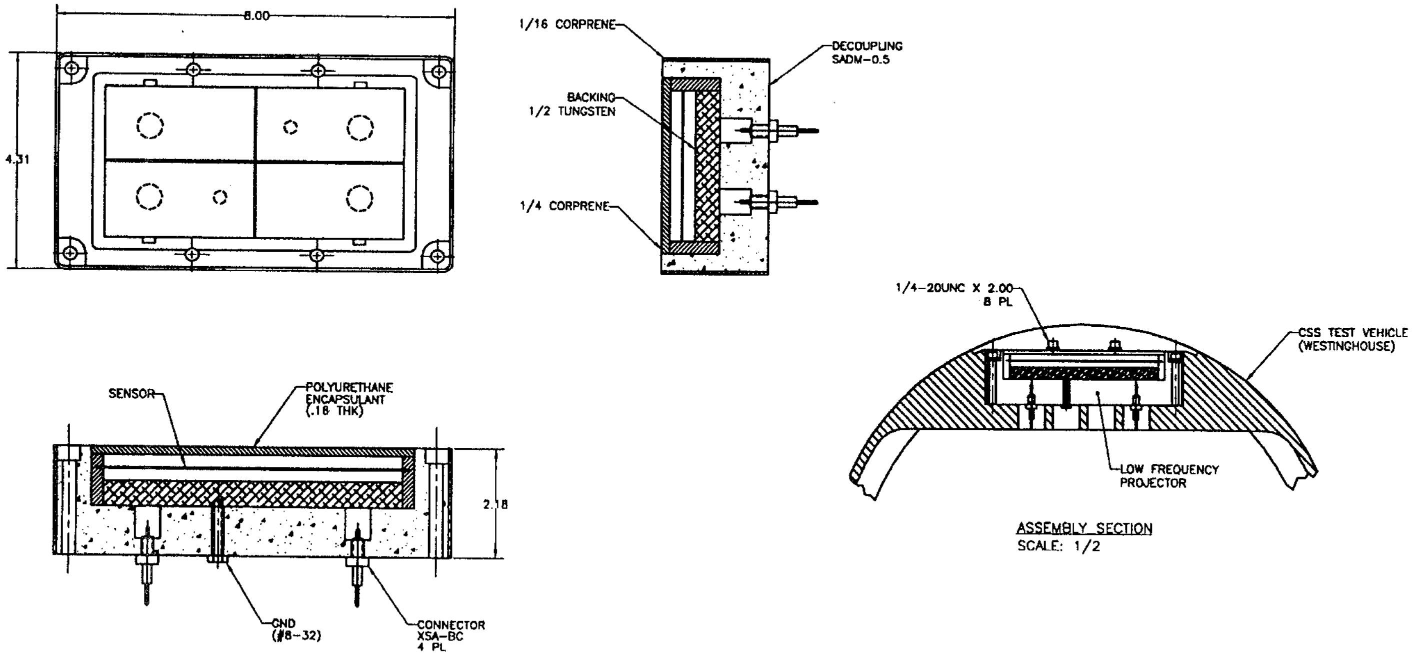

Fig. 1: Assembly drawing of the NRL projector.

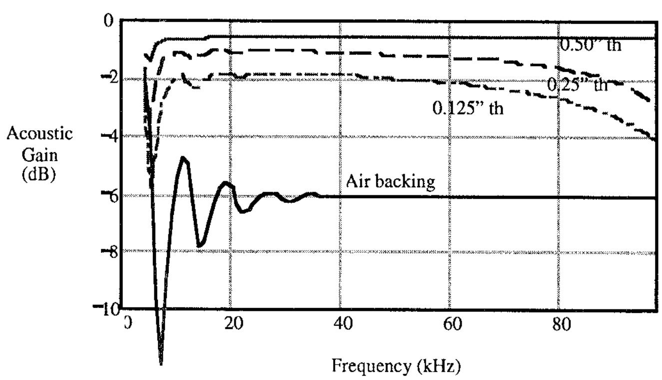

Fig. 2: Influence of tungsten backing thickness on acoustic source output gain of projector.

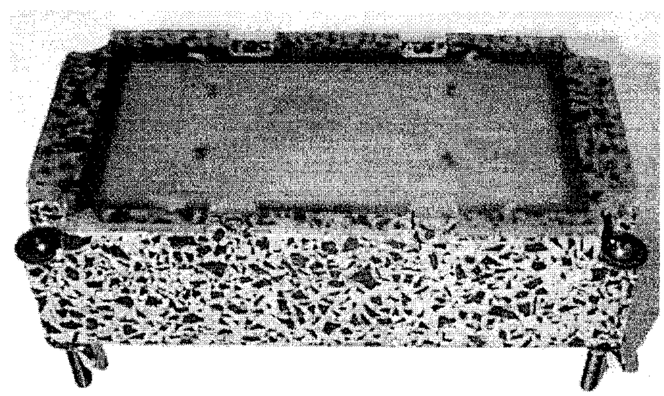

Fig. 3: Photograph of the top/side of the completed projector prototype.

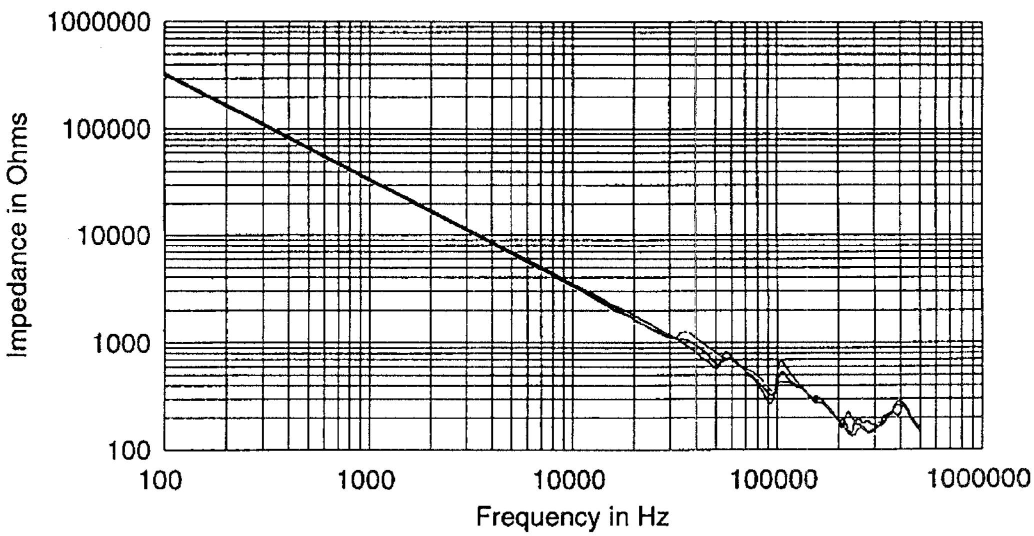

Fig. 4: Measured in-air electrical impedance magnitude response of each aperture element.

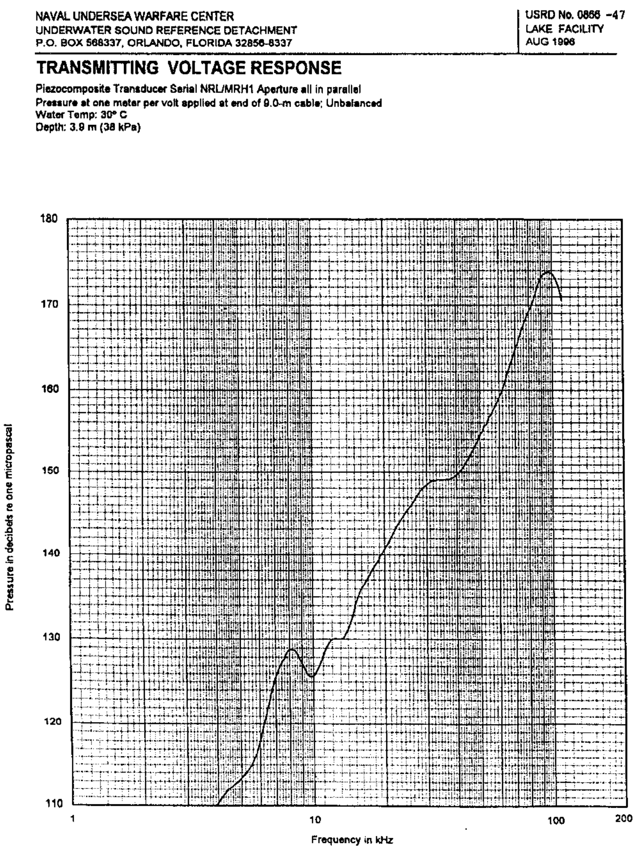

Fig. 5: Measured in-water free-field transmitting voltage response [3].

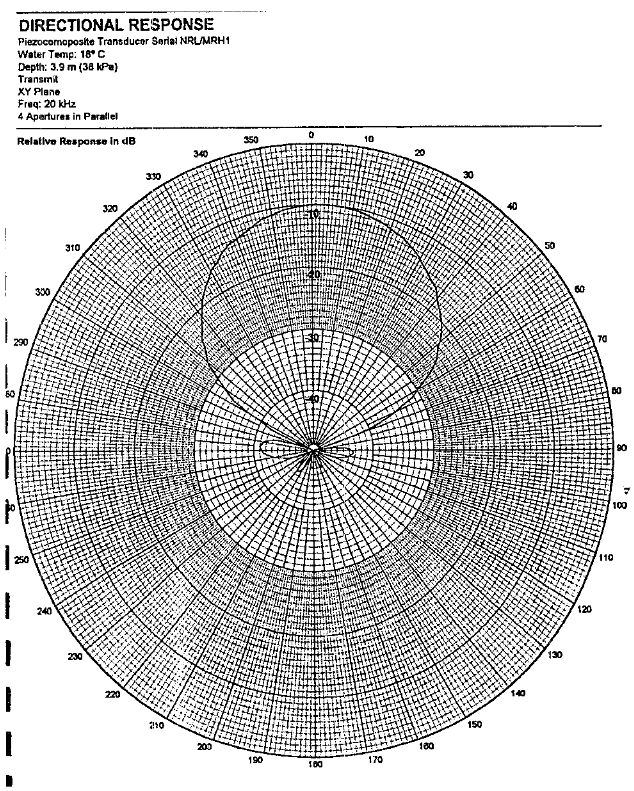

Fig. 6: Measured free-field transmitting directivity response at 20 kHz in the horizontal plane [3].